Crown Morphology of Norway Spruce from Usual Tree Measurements

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Abstract The crown morphology of Norway spruce (*Picea abies* Karst) was studied from 617 sample trees. In order to model branch and crown descriptors the linear and nonlinear regression methods were extensively used. Results show that the branch length can be fairly well predicted from the distance to the apex of the tree and that the branch spread has a high correlation with the branch length and the insertion angle. Models have been set up to predict the crown ratio, height to the base of the living crown, height to the first living branch and the height to the first dead branch from the usual whole-tree measurements, namely diameter at breast height, total height and total age.

Key words: Crown morphology, Branchiness, Crown ratio, Norway spruce, *Picea abies* Karst, Modeling, Wood quality.

Introduction

Norway spruce (*Picea abies* Karst) is one of the most important conifer in France. In 1991, the total area of Norway spruce was estimated to be 723000 hm^2. Its volume was 127 million m^3. The annual volume increment was 5.74 million m^3. It is widely accepted that larger initial spacings should be used now. In 1940's, the density of the plantation ranged from 5000 to 10000 stems/hm^2. Now the initial density varies between 1000 to 2500 stems /hm^2. The largest spacing may be 650~800 stems /hm^2. So it has a significance to study the branch and crown development of Norway Spruce. There are two aims in this study. One is to set up a limbsize model that links usual tree measurements to the required inputs of a wood quality simulation software (SIMQUA: Leban et al, 1990). Another aim is to construct models that predict the main characteristics of the crown for Norway Spruce. The results of the present study will be integrated into a system for predicting the quality of the coniferous wood resources from the database of the French National Forest Survey (IFN: Inventaire Forestier National).

Materials and Methods

Data collection

Three datasets were used. Dataset 1 contains 141 trees of Norway Spruce, four subsamples which have been described in Colin and Houllier (op. cit. 1992). Dataset 2 contains 452 trees sampled and measured by the Institute for Forestry Development (IDF: Institut pour le Developpement Forestier). Dataset 3 contains 24 sample trees measured in the context of an EEC (European Economic Community) contract. Their attributes are presented in Table 1.

Variables

Three types of variables were used: "branch descriptors", "whole tree descriptors" and "crown descriptors". The latter two are the usual tree measurements and different crown heights and crown ratios. Variables are:

Branch descriptors :

X=absolute distance from the upper bud scale scars of the annual shoot to the top of the stem, cm;

$ANGLE$= external insertion angle of the branch with the stem, in degree;

BL=branch length, cm;

BS=branch spread, cm.

Tree descriptors:

A=total age of the tree, years;

D=diameter of the stem at breast height, cm;

H=total height of the stem, m;

D/H=ratio between D and H, cm/cm.

Crown descriptors:

HFC=height to the first contact, m;
HFLB=height to the first living branch, m;
HFDB=height to the first dead branch, m;
HFLC=height to the base of the living crown, m;
CD=maximum crown diameter, m;
$CR=100(H\text{-}HFLC)/H$, %;
$CR1=100(H\text{-}HFLB)/H$, %.

Table 1. Attributes of 24 sample trees

age	*D*	*H*	*CD*	*HFDB*	*HFLB*	*HFLC*	*HFC*
53	38.0	27.25	4.46	1.95	11.95	15.75	21.75
53	38.0	28.25	4.56	2.00	12.40	14.10	19.70
53	31.5	26.67	3.74	2.30	13.85	16.40	21.00
53	34.0	27.70	4.50	2.15	15.35	17.30	20.55
53	26.5	26.06	4.32	1.85	14.40	15.5	23.00
53	27.5	25.48	3.94	2.25	14.05	14.90	21.00
53	31.0	29.13	4.08	2.15	15.30	19.10	24.50
53	28.5	28.79	3.38	2.05	19.55	21.5	24.55
53	30.0	29.10	3.94	2.15	19.20	20.15	22.25
53	34.0	28.56	3.60	1.75	16.50	19.00	23.55
53	26.5	28.20	3.70	2.30	15.40	19.35	25.20
53	33.0	28.84	5.24	1.80	16.20	18.60	22.25
63	30.0	25.05	4.24	2.40	10.20	13.60	21.00
63	45.5	25.24	4.76	2.70	9.05	11.65	19.80
63	32.5	25.30	4.20	2.15	9.75	16.20	21.75
63	35.0	24.74	4.64	2.65	7.75	14.35	18.70
63	43.5	27.80	4.08	2.45	14.80	16.90	21.70
63	38.0	27.30	4.38	2.70	10.20	16.15	21.50
63	33.0	23.70	4.16	2.35	12.45	14.05	18.25
63	32.0	26.26	4.22	2.35	12.35	15.55	20.15
63	34.5	27.07	3.92	2.50	16.05	17.05	21.35
63	38.0	26.05	4.84	1.90	13.50	14.30	21.05
63	31.5	25.93	3.70	2.20	12.45	15.30	21.45
63	38.0	26.07	4.12	2.15	10.85	15.30	22.30

where: *CD*=maximum crown diameter, m;
D=diameter of the stem at breast height, cm;
H=total height of the stem, m;
HFC=height to the first contact, m;
HFLB=height to the first live branch, m;
HFDB=height to the first dead branch, m;
HFLB=height to the base of the live crown,m.

Models

In order to select the optimal model, several kinds of models were used. Referencing to others studies (Mitchell, 1975; Kajihara, 1975, 1976, 1977; Dyer et al, 1987; Hashimoto, 1990, 1991; Ottorini, 1991; Colin et al, 1991, 1992),the following models were used.

Models for branch length:

$$BL=a(1\text{-}\exp(\text{-}b/aX))^{c} \quad (1)$$
$$BL=aX^{0.75}\text{-}bX\exp(\text{-}cX) \quad (2)$$
$$BL=a\ln(\text{-}b/aX+1) \quad (3)$$
$$BL=aX^{b}\exp(\text{-}cX) \quad (4)$$
$$BL=a\exp(\text{-}bX) \quad (5)$$

Models for branch spread:

$$BS=a+bBL\sin(ANGLE) \quad (6)$$
$$BS=(a+b\exp(\text{-}cBL))BL \quad (7)$$
$$BS=a+b\,BL \quad (8)$$

Models for the height to the base of the living crown and to the first living branch:

$$HBLC \text{ or } HFLB=H\exp(\text{-}(aD/H+bAH^{2}+cH)) \quad (9)$$
$$HBLC \text{ or } HFLB=H\exp(\text{-}(aD/H+bAH^{2}+cH+dA)) \quad (10)$$
$$HBLC \text{ or } HFLB=H\exp(\text{-}(aD/H+bAH^{2}+cA)) \quad (11)$$
$$HBLC \text{ or } HFLB=H\exp(\text{-}(aD/H+bA^{1.5})H^{2}+cA^{1.5})) \quad (12)$$
$$HBLC \text{ or } HFLB=H(1\text{-}a\text{-}\exp(\text{-}bA^{1.5})H^{2}+cH/D+dH^{2}) \quad (13)$$

Models for the height to the first dead branch :

$$HFDB=a+b(H\text{-}130)/D+cA^{1.5}H+dA^{1.5}D \quad (14)$$
$$HFDB=a+bH/D+cAH+dAD \quad (15)$$

Models for the crown ratio :

$$CR=100(1\text{-}\exp(\text{-}(aD/H+bAH^{2}+cH))) \quad (16)$$
$$CR \text{ or } CR1=100(a+\exp(\text{-}bA^{1.5})+cH/D) \quad (17)$$
$$CR \text{ or } CR1=100(a+\exp(\text{-}bA^{1.5})+cH/D+dA^{1.5}D) \quad (18)$$
$$CR1=100(1\text{-}\exp(\text{-}(aD/H+bAH^{2}+cH+dA))) \quad (19)$$

where: *a*, *b*, *c* and *d* are the parameters to be estimated.

Statistical analysis

With SAS (Statistical Analysis System, versions 6.0) (SAS Institute, 1988) package, linear and nonlinear regression methods have been extensively used. The proposed equations were chosen as compromises between (i) the search of a good fit as measured by adjustment statistics and by a visual analysis of residuals and (ii) the parsimony and the robustness of the model (i.e. we tried to avoid a too great number of parameters).

The following results include parameter estimates, their standard error, and their 95%-confidence interval, root mean squared error (RMSE) or weighted mean squared error (WMSE), adjusted Rsquare ($R_{adj}^{2}=1\text{-}((n\text{-}1)/(n\text{-}p))(1\text{-}R^{2})$) and weighting expressions.

Results

Crown shape and size relations

Crown shape and size result from the relationship between crown extension (i.e. branch growth) and height

growth. The branch growth involves in branch length (BL),branch spread(BS) and branch diameter. Branch diameter is not discussed here.

Branch length (BL)

By fitting equations (1) to (5), we have found that equation (1) is the best n tree top to the first contact , to the base of the living crown and to the first presented in Table 2.

Branch spread (BS)

Branch spread has a linear relationship with branch length and the sine of the insertion angle. By computing, equation (6) is the best. Parameter estimates for the equation (6) are given in Table 3.

Table 2. Parameter estimates for models of branch length

Position	Dataset	n	Weight	Parameter estimates	Asymptotic standard error	Asymptotic confidence interval 95% lower	Asymptotic confidence interval 95% upper	WMSE	R_{adj}^2
				a=287.4455	6.8154	274.0383	300.8508		
	dataset 3	340	$1/x^{1.5}$	b=0.4403	0.3990	0.1554	1.7251	1.252	0.93
first contact				c=1.4500	0.6224	0.2257	2.6743		
eq (1)				a=296.8712	17.4553	262.6250	331.1175		
	dataset 3 + dataset 1	1229	$1/x^{1.5}$	b=0.7334	0.0855	0.5656	0.9012	1.144	0.83
				c=1.1895	0.1159	0.9621	1.4170		
				a=312.6960	8.4241	296.1497	329.2423		
	dataset 3	574	$1/x^{1.5}$	b=0.9027	0.0350	0.8339	0.9716	1.203	0.95
base of crown				c=1.3998	0.0440	1.3135	1.4862		
eq (2)				a=271.1266	5.5649	260.2138	282.0394		
	dataset 3 + dataset 1	2406	1/x	b=0.8104	0.0322	0.7472	0.8736	0.905	0.84
				c=1.2739	0.0435	1.1888	1.3592		
				a=303.6293	5.5501	292.7320	314.5266		
	dataset 3	691	$1/x^{1.5}$	b=0.9316	0.0317	0.8713	0.9918	1.033	0.95
first living branch				c=1.4339	0.0400	1.3555	1.5124		
eq (2)				a=272.0651	3.7259	264.7594	279.3708		
	dataset 3 + dataset 1	2906	$1/x$	b=0.8106	0.0261	0.7594	0.8619	1.089	0.85
				c=1.2744	0.0369	1.2024	1.3592		

From a static point of view, equations (1) and (6) are an expression of crown shape and size. As for a give X varies with tree height in association with height growth , these equations reflect the process of expansion of the parts of a crown.

Table 3. Parameter estimates for the prediction of branch spread (equation (6))

Dataset	Weight	Parameter estimates	Asymptotic standard error	WMSE	R_{adj}^2
dataset 3	$1/(BL.\sin(ANGLE))$	a=0.81528	0.00393	6.630	0.98
dataset 1	$1/(BL.\sin(ANGLE))$	a=0.75614	0.00465	17.376	0.99
dataset 3 + dataset 1	$1/(BL.\sin(ANGLE))$	a=7.8821	0.00324	4.719	0.98

Models of main crown characteristics

Global description of the crown The dependent variables were height to the first dead branch ($HFDB$),height to the first living branch ($HFLB$), height to base of the living crown ($HBLC$) and crown ratio (CR).

The independent variables were total height (H),total age (A),diameter at breast height (D) and various combinations of these variables such as: $1/H$, H^2, H/D, D/H, $A\ H$, $A\ D$, etc....

Height to the base of living crown($HBLC$) The best individual predictors are A, D/H and H. By fitting equations (9) to (13), equation (9) is the best model for $HBLC$. In order to take into account the fact that the data set includes both data for isolated trees and data for trees belonging to the same stand, the weight of

each tree was inversely proportional to the number of trees belonging to the same stand. This weighting procedure led to a good fit especially for the data collected on old isolated trees.Parameter estimates are presented in Table 4.

Height to the first living branch(*HFLB*) We used the same method (equation and weighting expression) as for *HBLC*. We have found equation (10) is the best model for predicting *HFLB*. As previously, the weight expression took into account the number of sampled trees in each stand. Parameter estimates are showed in Table 5.

Table 4. Parameter estimates for the prediction of height to the base of the living crown (equation (9))

Dataset	Parameter estimates	Asymptotic standard error	Asymptotic confidence interval 95%		WMSE	R_{adj}^2
			lower	upper		
	a=68.90176	5.84732	57.33747	80.46606		
dataset 1	b=-5.6*10^{-6}	6.2*10^{-7}	-6.8*10^{-6}	-4.4*10^{-6}	0.0090	0.75
	c=-0.00147	0.00397	-0.00932	0.00638		
	a=35.61325	4.10335	27.54785	4367865		
dataset 2	b=-6.0*10^{-5}	9.0*10^{-6}	-7.7*10^{-5}	-4.2*10^{-5}	0.0011	0.61
	c=0.04114	0.00637	0.02862	0.05366		
	a=62.20247	2.44511	57.40020	67.00474		
all*	b=-5.8*10^{-6}	3.5*10^{-7}	-6.4*10^{-6}	-5.1*10^{-6}	0.0030	0.79
	c=0.00209	0.00180	-0.00145	0.00563		

* all=dataset 1+ dataset 2 + dataset 3

Table 5. Parameter estimates for the prediction of height to the first living branch (equation (10))

Datase	Parameter estimates	Asymptotic standard error	Asymptotic confidence interval 95%		WMSE	R_{adj}^2
			lower	upper		
	a=101.63831	11.12893	79.62850	123.6481		
dataset 1	b=-8.5*10^{-6}	2.7*10^{-7}	-1.3*10^{-6}	-3.2*10^{-6}		
	c=0.00356	0.00672	-0.01684	0.00973	0.0106	0.58
	d=0.00296	0.00227	-0.00154	0.00745		
	a=104.38967	10.20408	84.23645	24.54290		
	b=-9.1*10^{-6}	2.4*10^{-7}	-1.4*10^{-6}	-4.3*10^{-6}		
dataset 1 + dataset 3	c=0.00683	0.00594	-0.01856	0.00490	0.0094	0.61
	d=0.00371	0.00210	0.00044	0.00787		

Height to the first dead branch(*HFDB*) The statistical analysis was carried out on 80 trees in data 1 (pruned trees were removed). Models for *HBLC* and *HFLB* were first tested but the best results were obtained with a linear model (equation 14) including $H \cdot A$, H/D and $D \cdot A$. Parameter estimates for equation (14) are given in Table 6.

Crown ratio(*CR*) Since $CR=100 \cdot (H\text{-}HBLC)/H$ and $CR1=100 \cdot (H\text{-}HFLB)/H$ and best models for *HBLC* and *HFLB* are equation (9) and equation (10) respectively, we finally got equation (16) and equation (19). By fitting equations (16 to (18), equation (16) is the best model for *CR*. By fitting equations (17) to (19), equation (19) is the best model for *CR*1. Parameter estimates for equation(16) and equation (19) are the same as in table 4 and in Table 5 respectively.

Table 6. Parameter estimates for the prediction of height to the first dead branch (equation (14))

Dataset	Parameter estimates	Asymptotic standard error	Asymptotic confidence interval 95%		WMSE	R_{adj}^2
			lower	upper		
	a=-77.58979	36.65005	-150.58491	-4.59466		
	b= 1.64623	0.47344	0.70328	2.58918		
dataset 1	c=-5.7*10^{-5}	3.2*10^{-5}	-1.2*10^{-4}	7.3*10^{-6}	0.00081	0.50
	d= 0.00023	0.00006	-0.00011	0.00036		

Conclusion

These models provide a comprehensive and consistent framework for predicting branchiness and crown characteristics from usual tree measurement as those available from local management or the database of the French National Forest Survey.

Above results show that: (1) The branch length has a high correlation with the distance from the tree top. The size of whorl branch may be predicted at any point along the stem; (2) The main characteristics of the crown may be estimated from usual tree measurements, such as total age, total height and diameter at breast height, etc.. (3) The weightiness is available on modeling the shape of the crown.

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